1

# CAPACITIVELY COUPLED POWER SUPPLY

## RELATED APPLICATIONS

[0001]    The present application claims priority under 35 U.S.C. § 119 of Provisional Patent Application Serial Number 60/418,823 filed on October 16, 2002.

5                    ## FIELD OF THE INVENTION

[0002]    The present invention relates to power supplies in general, and more particularly, to generating a supply voltage using capacitive coupling in a main current path.

## BACKGROUND OF THE INVENTION

[0003]    Power supplies serve the purpose of converting an input voltage into one or
10    several output voltages.  An AC power source may be used to provide an AC power line input, which gets converted to a DC regulated output voltage.  Transformers are typically used to provide isolation between a "hot" ground and a "cold" ground for a power supply or a converter.  A primary winding of a transformer typically conducts a non-isolated direct current (DC). In the event of a overloading, the current in the primary winding might be,
15    disadvantageously, excessive and may damage, for example, a power transistor that drives the transformer. Additionally, transformers are typically large in size (due to the size of the magnetic elements within them), bulky and expensive devices. It may be desirable to have a power supply that is inherently short circuit protected in a manner that avoids using dedicated circuit components.

20    [0004]    In carrying out an inventive feature, a regulated power supply utilizes capacitive elements to transform an input voltage from, for example, a DC power source to a specified output voltage level across a load. The capacitive element, advantageously, could provide capacitive isolation between a "hot" ground and a "cold" ground.

## SUMMARY OF THE INVENTION

25    A power supply, embodying an inventive feature, includes a supply inductor and a first capacitor coupled to form a resonant circuit to generate a resonant waveform in a resonant operation, during a first portion of an operation cycle of the power supply. A charge storage element develops an output voltage to energize a load. A rectifier is coupled to the charge storage element and to the resonant circuit and is responsive to the resonant waveform for
30    applying the output voltage back to the resonant circuit to interrupt the resonant operation, at

2

an end time of the operation cycle first portion, when the resonant waveform produces a first change of state in the rectifier. A first sensor senses when the first change of state in the rectifier occurs. A source of a supply current is coupled to the rectifier and rectified in the rectifier to produce a rectified current that is coupled to the charge storage element to replenish a charge therein, during a second portion of the operation cycle. A switching transistor is responsive to an output signal of the first sensor for enabling the supply current to be coupled to the rectifier, during the operation cycle second portion, and for disabling the supply current from being coupled to the rectifier, during the operation cycle first portion.


BRIEF DESCRIPTION OF THE DRAWINGS

[0005]    Figure 1 shows a power supply with capacitive mains isolation in accordance with an embodiment of the present invention;

[0006]    Figures 2a, 2b, 2c, 2d, 2e and 2f show waveforms associated with the operation of the power supply shown in Figure 1;

[0007]    Figures 3a, 3b and 3c show three equivalent circuits of the power supply of Figure 1 during three separate intervals, respectively, of a period of operation of Figures 2a-2f;

[0008]    Figure 4 shows a power supply operating using inventive features of the power supply of Figure 1 and in more details;

[0009]    Figures 5a, 5b and 5c show waveforms associated with the operation of the power supply shown in Figure 4 for a first load;

[0010]    Figures 6a, 6b and 6c show waveforms associated with the operation of the power supply shown in Figure 4 for a load higher than the first load;

[0011]    .Figure 7 illustrates a graph showing an example of the variation of the efficiency of the power supply of Figure 4 as a function of the output power; and

[0012]    Figure 8 illustrates schematically a manner by which an immunity against radio frequency interference (RFI) is obtained with the power supply of Figure 4.

DETAILED DESCRIPTION

Figure 1 illustrates a power supply 300, partially in a schematic form, with capacitive mains isolation, embodying an inventive feature. An input supply voltage Vin referenced to a

3

"hot" ground conductor 50 is produced in, for example, a conventional bridge rectifier, not
shown, and is non-isolated from "hot" ground conductor 50. Voltage Vin is coupled via a
supply inductor L1 to a terminal 302 of a switch S1 formed by a switching power transistor,
not shown, that is controlled by a control circuit 301 to switch a high frequency. Terminal 302

5     is coupled to ground conductor 50 when switch S1 is conductive.

When switch S1 is non-conductive, terminal 302 is coupled to ground conductor 50
via a series arrangement of a first isolation capacitor C1, a second isolation capacitor C2, a
second supply inductor L2 that is coupled between capacitors C1 and C2 and a current
sampling resistor Rtrig2. Current sampling resistor Rtrig2 is coupled between capacitor C2

10    and ground conductor 50. When switch S1 is non-conductive, terminal 302 is also coupled to
ground conductor 50 via a series arrangement of a capacitor Ctrig and a current sampling
resistor Rtrig1. Current sampling resistor Rtrig1 is coupled between capacitor Ctrig and
ground conductor 50. A rectifier diode D1 and a filter capacitor C3 form a series arrangement
that is coupled across inductor L2 for developing a rectified output supply voltage Vout in

15    capacitor C3 forming a charge storage element. A load resistor RL is coupled in parallel with
capacitor C3 and energized by voltage Vout. Voltage Vout is isolated with respect to electrical
shock hazard from ground conductor 50 by the high impedance at low frequencies of
capacitors C1 and C2.

An anode of diode D1 is coupled to a junction terminal 303 between capacitor C1 and

20    inductor L1. A terminal of capacitor C3 that is remote from a cathode of diode D1 forms a
"cold" ground conductor 51. Voltage Vout that is referenced to "cold" ground conductor 51 is
isolated with respect to electrical shock hazard from ground conductor 50. A terminal of
inductor L2 that is remote from diode D1 and a terminal of capacitor C2 that is remote from
resistor Rtrig2 also are at the reference potential of "cold" ground conductor 51.

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[0013]    Capacitors C1 and C2 provide ground isolation due to the fact that the
capacitors have a high impedance at the relatively low frequency of Vin. However, the
capacitors represent a low impedance at the relatively high frequency of operation of switch
S1, which is at a higher frequency than that of voltage Vin. Switch S1 is responsive to a

30    control signal 62 from control circuit 3 for selectively opening/closing the connection
between terminals 302 and 50 to disable/enable application of the input supply voltage Vin
to inductor L1. In this manner the switch is operated cyclically at a given frequency f in
accordance with the control signal. Capacitors C1 and C2 have low impedance with respect

4

to this frequency. For example, capacitors C1 and C2 may have a low impedance in relation
to operation of switch S1 at 50KHz, while providing a high impedance and isolation at an
input voltage Vin of, for example, 50Hz or 60Hz. Power supply 300 is a self-oscillating
power converter, which is optimized for maximum energy transfer at minimum switching
loss.

[0014]    An operating cycle or a period T of power supply 300 can be divided in three
time intervals T1, T2 and T3, shown in Figures 2a-2f, for a value of inductor L1 of Figure 1
equal to twice that of inductor L2. Similar symbols and numerals in Figures 1 and 2a-2f
indicate similar functions or items. Figure 3a represents the equivalent circuit to the circuit
of Figure 1 during interval T1 of Figure 2a-2f. Similar symbols and numerals in Figures 1,
2a-2f and 3a indicate similar functions or items.

During interval T1 of Figures 2a-2f, switch S1 of Figure 1 is conductive. Capacitors
C1 and C2 are charged during interval T2 of Figures 2a-2f, as described later on. After
closing switch S1 of Figure 1, during interval T1 of Figures 2a-2f, a current IL1 of Figure 2b
rises linearly and energy is stored in inductor L1 of Figure 1. At the same time, a current IL2
of Figure 2d in inductor L2 of Figure 1, forming a resonant circuit 305 of Figure 3a with
capacitors C1 and C2 of Figure 1, goes negative sinusoidally in a resonant manner and the
energy previously stored in capacitors C1 and C2 is transferred in a resonance manner to
inductor L2 in the form of current I2.

At the end of interval T1 of Figures 2a-2f, voltage V2 of Figure 2e becomes equal to
voltage Vout of Figure 1 causing diode D1 to become conductive. Consequently, a sum of
voltages in capacitors C1 and C2 is clamped to voltage Vout and current I2 changes abruptly
to become zero. Thus, capacitors C1 and C2 are discharged to a maximum extent and a
voltage V2 of Figure 2e in inductor L2 of Figure 1 becomes equal to voltage Vout. At the
beginning of interval T2 of Figures 2a-2f, diode D1 of Figures 1 is, consequently,
conductive. Therefore, the voltage across sensor resistor Rtrig2 of Figures 1 approaches zero
volts. When the voltage across resistor Rtrig2 becomes zero, control circuit 301 turns off
switch S1 via signal 62. Advantageously, by turning switch S1 on immediately after diode D1
becomes conductive, the possibility of a "dead time" in the period T of Figures 2a-2f, that
does not contribute to the throughput via capacitors C1 and C2, is avoided.

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Figure 3b represents the equivalent circuit to the circuit of Figure 1, during interval T2 of Figure 2a-2f. Similar symbols and numerals in Figures 1, 2a-2f and 3b indicate similar functions or items. During interval T2 of Figures 2a-2f, switch S1 of Figure 1 is turned off. Conductive diode D1 and capacitor C3 form effectively a negligible low impedance because capacitor C3 has a much larger value than the other capacitors. Capacitors C1 and C2 and Ctrig are charged via inductor L1 until, at the end of interval T2, voltage V1 of Figures 2a reaches a maximum value and current I2 of Figures 2c becomes zero. At this instant almost all energy present in the circuit is stored in capacitors C1 and C2.

Figure 3c represents the equivalent circuit to the circuit of Figure 1, during a following interval T3 of Figures 2a-2f. Similar symbols and numerals in Figures 1, 2a-2f and 3c indicate similar functions or items. During interval T3 of Figures 2a-2f, a trigger signal 62 for turning on switch S1 of Figure 1 is produced. During interval T3 of Figures 2a-2f, capacitors C1 and C2 of Figure 1 can be neglected since their values are much larger than that of capacitor Ctrig. Capacitor Ctrig forms a parallel resonance circuit 304 of Figure 3c with inductors L1 and L2, and a half cycle of oscillation occurs. Voltage V1 reaches its minimum at the end of interval T3 and current IL2 returns to zero. At the end of interval T3, a voltage developed across current sampling resistor Rtrig1 of Figure 1 changes polarity from negative to positive. This zero crossing transition is sensed and causes control circuit 301 to turn on switch S1. Advantageously, the switching losses are negligible, because voltage V1 is at a minimum. All capacitors are part of a resonant network, which prevents the presence of high dv/dt's, thus ensuring a high efficiency.

Figure 4 illustrates a power supply 400 in details that is similar to that of Figure 1. Similar symbols and numerals in Figures 1, 2a-2f and 3a-3c and 4 indicate similar functions or items.

Components L1, L2, C1 , C2, S1, D1 and C3 of Figure 4 perform the same functions as in Fig. 1 . Inductor L2 is tapped in order to transform voltage Vout to lower levels. At the mains connection side an additional line filter 601 is implemented to guaranty the required isolation between the primary and the secondary side. Therefore, the line filter inductor establishes a high asymmetrical attenuation at the operation frequency. The internal drain to

6

source capacitance of transistor switch S1 is used to perform the function of capacitor Ctrig of Figure 1.

In a first embodiment, power supply 400 of Figure 4 generates an output power of
5    25W with an input voltage of 115V AC. In a second embodiment, power supply 400 of Figure 4 generates an output power of 100W with an input voltage of 230V AC. Only switch S1 and the tap ratio of inductor L2 are different. The power transferred by power supply 400 is given by: $P = Vc12 \cdot$ (the value of capacitor C1) $\cdot$ f if the value of capacitor C2 equal to that of capacitor C1, Vc1 is the voltage across C1 and "f" is the switching frequency.

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The transformation ratio depends on the ratio of the inductances of inductors L1 and L2 and the duration of interval T3. This ratio can be increased by providing inductor L2 with a tap 401. The converter consists of a power oscillator 401 and a burst mode controller 402. Oscillator 401 runs at about f=300 kHz. When a comparator IC2 of burst mode controller 402
15    senses nominal output voltage, oscillator 401 is turned off by interrupting the power to the oscillator via an opto-coupler IC1 and a transistor Q8. A lower voltage at the output turns it on again. Thus the power supply operates in burst mode. The interval between the bursts varies with input voltage and load. Maximum power output is obtained when the oscillator is continuously on. The relation between efficiency and output power is shown in Figure 7.

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A supply voltage 404 of the control circuit is generated by a charge current through a filter capacitor Cmains via a diode D12 and a capacitor C7 that forms a capacitive voltage divider with capacitor Cmains. The circuit includes a transistor Q9, a transistor Q10 and a reference voltage diode D11 that limit the voltage across capacitor C7 to 20V.

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A transistor Q7, a transistor Q8, an opto-coupler IC1 and a comparator IC2 act as an on/off switch for the supply voltage of oscillator 401 to control the duration of a burst. A resistor R10 and a diode D10 enable initial start-up of power oscillator 401. Transistors Q7 and Q8 turn on with a fast rising edge causing switch S1 to turn on via transistor Q3.
30    Transistor Q6 turns on at the same edge, but because of a time constant of a capacitor C5 and a resistor R6 it turns off a few microseconds later. This turns on transistor Q2 and switch transistor S1 is switched off. This arrangement is used to guarantee a proper start-up of the oscillator. As a result, interval T2 of Figures 2a-2f is initiated.

The energy stored in inductor L1 during the on-time of switch S1 (analogous to interval T1 of Figures 2a-2f) charges capacitors C1 and C2 of Figure 4 with a current of sinusoidal shape (similar to current IL1 of Figure2b), which flows also through secondary

5   rectifier D1 of Figure 1.

When switch S1 becomes non-conductive, the internal drain-source capacitance of the transistor that implements switch S1, which acts as capacitor Ctrig of Figure 1, is connected in parallel to the series connection of capacitors C1 and C2. When the current through diode D1

10  becomes zero, a high frequency resonance circuit including capacitor Ctrig, and inductors L1 and L2 operate in a resonance manner. This is analogous to interval T3 of Figures 2a-2f. A current flowing through diodes D3, D4 and D5 of Figure 4 keeps transistors Q4 and Q5 off during a half cycle of resonant oscillation. As soon as this current changes polarity, transistors Q4 and Q5 turn on. Consequently transistor Q2 turns off and transistor switch S1

15  is turned on via transistor Q3. Transistors Q4 and Q5 act as a current sensor. Transistor Q4 is kept on by the current through transistor switch S1.

When the energy in capacitors C1 and C2 has been transferred to inductor L2, the voltage across inductor L2 reaches a magnitude that causes secondary diode D1 to turn on and

20  the current in capacitor C2, for example, ceases. The current through switch S1 and inductor L1 flows through diode D6 instead of through capacitor C2 and turns on transistor Q2. Thus, diode D6 and transistor Q2 form a current sensor for turning transistor switch S1 off. The procedure will repeat itself as described until burst mode controller 402 turns off the supply of oscillator 401.

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Figures 5a, 5b and 5c show waveforms associated with the operation of the power supply shown in Figure 4 for load resistor RL equal to 7.5 Ohm; whereas, Figures 6a, 6b and 6c show waveforms associated with the operation of the power supply shown in Figure 4 for a higher load formed by resistor RL equal to 1 Ohm. Similar symbols and numerals in Figures

30  -1, 2a-2f, 3a-3c, 4, 5a-5c and 6a-6c indicate similar functions or items.

If oscillator 401 operates continuously and not in burst mode, and the load, not shown, increases still further as a result of a fault condition, output voltage Vout will drop. As a

result, interval T1 of Figures 2a-2f increases, the oscillator 401 frequency decreases and the level of voltage V1 of Figure 6c will be lower than before at the beginning of interval T3 of Figures 2a-2f. In this way the amount of transferred energy, advantageously, decreases significantly. This tendency remains until the short-circuit condition is reached. Thus the

5 circuit protects itself against overload.

Power supply 400 of Figure 4 also guarantees a soft start-up. Interval T1 of Figures 2a-2f decreases gradually and likewise the frequency and the transferred energy increase until the required level of output voltage Vout is reached. As shown in Figures 4 and 8, a line filter

10 600 is provided for RFI suppression and safety. The filter inductor 601 of Figure 4 establishes a high symmetrical attenuation at the operating frequency of oscillator 401. An inductor of 20mH fulfils the required attenuation up to 50W. During experiments, a considerable temperature increase of the capacitors C1 and C2 was observed. The selection of the proper type and construction of these capacitors is important. If capacitors C1 and C2 are selected

15 with a negative temperature coefficient, some inherent safety is provided, because the amount of transferred power and the temperature decrease with the capacitor value.